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Application of low-temperature area-selective regrowth for ultrashallow sidewall GaAs tunnel junctions

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Low-temperature (290 °C) area-selective regrowth by the intermittent injection of precursors in an ultrahigh vacuum was applied for the fabrication of ultrashallow sidewall GaAs tunnel junctions with the junction area in the order of 10^{-8} cm^2. The tunnel junctions on the normal mesa orientation have shown the record peak current density up to 31 000 A/cm^2 and negative differential conductance of -1.4×10^{-5} S at 100 μm long strip structure. The peak current density of tunnel junctions has shown strong sidewall orientation dependences with the order of {111}A>{110} >{111}B. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1510162]

High-quality tunnel junction is one of the important semiconductor segments for the application of millimeter and submillimeter wave source, and detectors, etc. Among the semiconductor submillimeter wave sources, the tunnel injection transit time effect diode (TUNNETT),[1] which is the transit time effect diode operated by the tunnel injection under the reverse bias, is one of the most promising submillimeter wave source up to terahertz region. In the TUNNETT diode, the most important factor is the quality of p^+n^+ tunnel junction. In order to improve the high frequency oscillation characteristics and low power dissipation, it is also required that the junction area has to be reduced in view of the impedance matching.[2] The resultant reduction of parasitics will improve the microwave device performances.

In this work, the low temperature area selective regrowth was applied to form the ultrashallow sidewall GaAs tunnel junctions with the junction area as small as 10^{-8} cm^2. The area-selective regrowth was achieved by the intermittent injection of triethylgallium and arsine in an ultrahigh vacuum at 290 °C.

The sidewall GaAs tunnel junctions have shown the record peak current density up to 31 000 A/cm^2, and the strong sidewall orientation dependences are discussed in view of the doping characteristics on various crystal orientations and the effects of traps at the tunnel junction interface.

The tunnel diodes were fabricated by the molecular layer epitaxy (MLE)[3] in an UHV. First, Te and S codoped n^+-GaAs was grown on {100} oriented semi-insulating (SI) GaAs at 360 °C. Precursors used for Te and S doping were diethyltelluride (DETe) and diethylsulfur (DES). In order to achieve high impurity concentration, DETe was exposed on the gallium stabilized surface (mode *AG*)[4] and DES was introduced on the arsenic stabilized surface (mode *AA*) during MLE growth cycles. Epitaxial layer thickness of n^+-GaAs is about 49 nm, which determines the junction depth of sidewall tunnel junctions. Te and S codoping[5] is effective to reduce the lattice strain in a heavily donor doped layer. Then, SiN is deposited at 275 °C. Windows were opened for area-selective regrowth by using conventional photolithography and the reactive ion etching (RIE). Through these windows, the sidewall mesa was formed by H_2SO_4-based solution with the depth of 60 nm. Then the patterned substrates with n^+ layer were loaded into the UHV growth chamber, and the surface treatment was carried out at 350 °C for 30 min under the AsH_3 pressure of 8×10^{-4} Torr. The area-selective regrowth of p^+-GaAs:Be was carried out at 290 °C using Be(MeCp)$_2$. Be(MeCp)$_2$ was introduced by mode *AG* to achieve high carrier concentration[6] of 8×10^{19} cm^{-3}. Figure 1 shows the schematic drawings of the cross sectional and top view of the fabricated sidewall tunnel junction diodes.

Figures 2(a)–2(c) shows the $J-V$ characteristics of GaAs sidewall tunnel junctions on various sidewall orientations. It is shown that the peak current density (J_p) on normal mesa orientation shows the highest value of 31 000 A/cm^2 at room temperature with the peak to valley ratio of 2.0. J_p of 45°-inclined configuration and that of reverse mesa orientation are 5200 and 2100 A/cm^2. The peak voltages (V_p) for normal mesa, 45°-inclined configuration and reverse mesa orientation are 214, 130, and 136 mV, respectively. Table I summarizes the present tunnel diode characteristics at nominal room temperature. It is shown that the peak, valley current density (J_p,J_v) and resultant peak-to-valley ratio (J_p/J_v) have shown strong mesa orientation dependences.

In heavily donor doped n^+-GaAs, it has been reported that the donor-defect complex center[7] is formed, and the excess current is dominated by the leakage current via states. In this case, the valley current density is expressed as[8]

$$J_{\text{valle}}\approx AD_x \exp\left\{-\frac{\pi}{2\hbar q}\sqrt{\frac{\varepsilon m_x^*}{N_{\text{eff}}^*}}[E_{\text{gap}}+0.35(\xi_n+\xi_p)]\right\},$$

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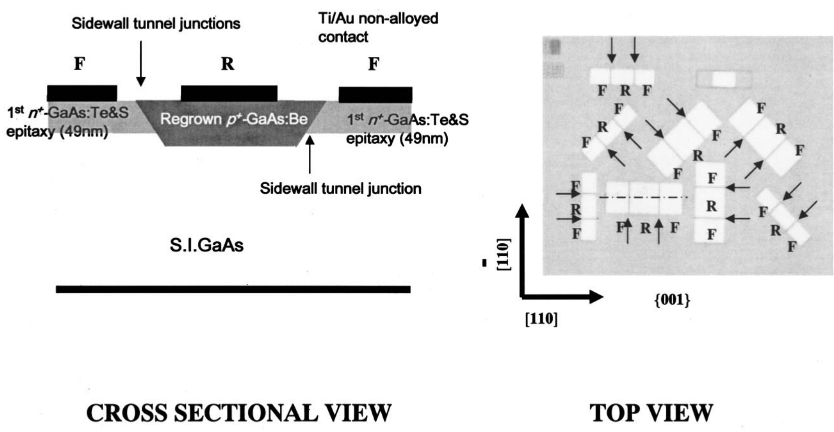

FIG. 1. Schematic drawings of the cross sectional and top view of the fabricated sidewall tunnel diodes. *F* and *R* mean the first epitaxial layers and the regrowth layers, respectively. The arrows indicate the positions of sidewall regrown tunnel junctions. The large pad has 100 μm in length, and the small one has 50 μm.

where the valley voltage is equal to $0.65(\xi_n+\xi_p)$, and D_x is the volume density of occupied levels at energy E_x above the top of the valence band and A is a constant under the assumption of $m_x^*=m_{\rm eff}^*$. $N_{\rm eff}^*$ and $m_{\rm eff}^*$ are the effective density of states and the tunneling effective mass, which are

$$N_{\rm eff}^*=\frac{pn}{p+n},\quad m_{\rm eff}^*=\frac{m_{lh}^*m_e^*}{m_{lh}^*+m_e^*}.$$

Therefore, the valley current density is dependent on the doping concentration (n,p). Thus, it is considered that one of the reasons for low J_p/J_v is the very high effective density of states $N_{\rm eff}^*$ in the present sidewall tunnel junctions.

In view of the mechanism for the strong sidewall orientation dependences on J_p, the Be-doping characteristics are investigated by using various surface orientations at the same epitaxial run under the identical conditions for device epitaxy. From the FE–SEM observations of deep etched trench (depth=200 nm), the sidewall orientations for normal mesa, 45°-inclined configuration and reverse mesa were determined to be nearly {111}A, {110} and {111}B. It is shown that Be concentrations are in the order {111}A:{111}B:{110} =1:0.8:0.2. J_p is affected by many parameters. After Kane[9] and Beji *et al.*,[10] J_p for the direct tunneling is obtained as

$$J_{\rm peak}=\frac{1}{36\pi\hbar^2}\sqrt{\frac{q^5m_{\rm eff}^*N_{\rm eff}^*V_0}{\varepsilon E_{\rm gap}}}\times\exp\left(-\frac{\pi}{2\hbar}\sqrt{\frac{\varepsilon E_{\rm gap}^3m_{\rm eff}^*}{q^3N_{\rm eff}^*V_0}}\right)D(qV_{\rm peak}),$$

where D is an integral in energy units, qV_0 is the built-in potential, and q is the electron charge, $\hbar$ is the reduced Plank's constant, $E_{\rm gap}$ is the band gap energy, and ε is the dielectric constant. In addition, in case of trap assisted or phonon assisted inelastic tunneling J_p is affected seriously by many parameters like trap density, occupation probability of traps,[11] deformation potential,[12] etc. The orientation dependence on effective tunneling mass[13] is also one of the important parameters, which determines J_v in the tunnel diodes. Actually, from Fig. 2, J_v ratios $J_v(290\ {\rm K})/J_v(77\ {\rm K})$ between 290 and 77 K are 2.1 for normal mesa and 45°-inclined configuration. However, that for reverse mesa, on which J_p and J_p/J_v are lowest, shows larger temperature dependence and to be 2.8. This indicates J_v is dominated by the tunneling through the midgap levels in the tunnel junction, especially on reverse mesa orientation.

The reason for the highest J_p on normal mesa orientation, which is nearly {111}A, can be understood partially in view of the Be doping characteristics. However, the reason for $J_p\{110\}>J_p\{111\}$B is still not clear. From the peak voltage V_p, the carrier concentration at the tunnel junction is estimated. The electron concentration of first epitaxial n^+-GaAs was about 2×10^{19} cm^{-3}. V_p is obtained by $(\xi_p+\xi_n)/3$. The degeneracy of $n(\xi_n)$ and $p(\xi_p)$ region are calculated from the expressions below[8] $n=N_c^*F_{1/2}(\xi_n/k_bT)$, $p=N_v^*F_{1/2}(\xi_p/k_bT)$ where $F_{1/2}$ is the Fermi integral of order 1/2 and N_c^* and N_v^* are the effective density of states in the conduction and valence bands. Under the assumption of fixed $n=2\times10^{19}$ cm^{-3}, the hole concentration at the tunnel junction interface can be estimated to be 2.4×10^{20} cm^{-3} for normal mesa, 5.9×10^{19} cm^{-3} for 45°-inclined configuration, and 6.8×10^{19} cm^{-3} for reverse mesa orientation. Whereas the absolute value is different, the magnitude order of estimated hole concentration corresponds well with the Be doping characteristics on each surface.

Whereas the actual doping profile on the sidewall surface cannot be obtained, the secondary ion mass spectroscopy (SIMS) measurements were performed for the plane structure on {001} surface under the identical epitaxial and regrowth process. Figure 3 shows the SIMS depth profile for the regrown p^+n^+ tunnel junction made on {001} surface. Whereas the actual impurity profile is more steep, it is shown that the Te and S profiles look very flat, and that the Be profile shows pile-up at the regrowth interface with the concentration up to 10^{20} cm^{-3}. It is noticed that this value corresponds well with the hole concentration estimated from V_p. From the SIMS profile, the actual doping profile has δ doping like structure of Be at the tunnel junction interface. This can be one of the reasons for this kind of very high J_p of the present tunnel diodes.

In conclusion, ultrashallow sidewall GaAs tunnel junctions were fabricated by the low-temperature (290 °C) area-selective regrowth by the intermittent injection of precursors in an ultrahigh vacuum. The tunnel junctions on the normal mesa orientation have shown the record J_p up to 31 000 A/cm^2 and differential negative conductance of -1.4×10^{-5} S at 100 μm long strip structure. Tunnel junction characteristics have shown strong sidewall orientation dependences due to the orientation-dependent Be doping characteristics and the midgap levels in the tunnel junctions. High concentration Be pile-up at the regrown interface is one

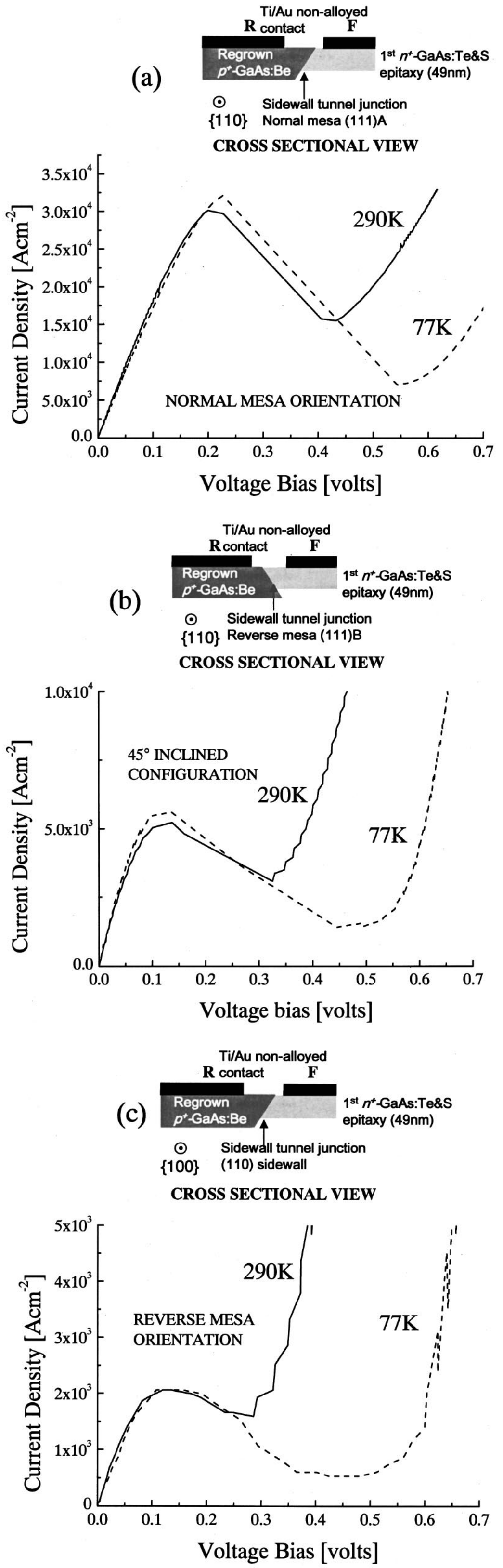

FIG. 2. $J-V$ characteristics of GaAs sidewall tunnel junctions at 290 and 77 K on (a) normal mesa, (b) 45°-inclined configuration, and (c) reverse mesa sidewall orientations.

of the possible reasons for extremely high J_p under the assumption that the interface pile-up phenomenon is similar for all sidewall orientations.

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TABLE I. Regrown sidewall tunnel junction characteristics at nominal room temperature.

	Normal mesa ~{111}A	45°-inclined configuration ~{110}	Reverse mesa ~{111}B
J_{peak} (A cm^{-2})	31 000	5200	2100
J_{valley} (A cm^{-2})	14 900	3110	1530
Peak-to-valley current ratio	2.08	1.67	1.37
V_{peak} (mV)	214	130	136
V_{valley} (mV)	414	282	252
V_{peak}/J_{peak} (Ω cm^2)	6.9×10^{-6}	2.5×10^{-5}	6.5×10^{-5}
Zero-bias specific resistivity (Ω cm^2)	5.3×10^{-6}	1.0×10^{-5}	2.9×10^{-5}
Negative differential conductance (S)	1.4×10^{-5}	7.1×10^{-5}	2.1×10^{-4}

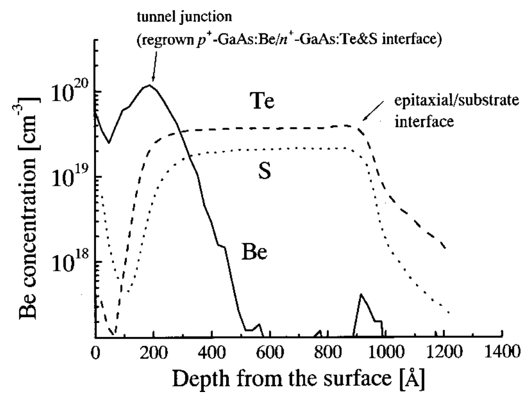

FIG. 3. SIMS depth profile for the regrown p^+n^+ tunnel junction made on {001} surface formed by the identical regrowth process and conditions as the sidewall junction.

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